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13. ABSTRACT *(Maximum 200 words)*
Research is reported in the following areas: [1] Transient and high-frequency enhancements of the scattering of sound by elastic objects in water are measured and analyzed. (The impulse response of a thick cylindrical shell in water was measured as a function of aspect angle. The measurements show the frequency locus of a backscattering enhancement extending to near end-on incidence in agreement with predictions for an antisymmetric leaky Lamb wave. Other enhancements and supporting theoretical developments are noted.) [2] New measurements and theoretical work on the interaction of sound with sound mediated by an aqueous suspension display coherent scattering effects for a range of conditions. [3] The coupling of an oscillating magnetic field to the quadrupole quasi-flexural mode of a shell in air is investigated. (An acoustic signature produced by shell vibrations in response to an oscillating Maxwell stress is easily detected even without the static bias magnetic field normally used in an EMAT.) [4] An oscillating electric field is used to excite the monopole mode of bubbles in an insulating liquid. (As with item (3), the method may be useful for measuring mode frequency and damping where exact solutions are not known.)

14. SUBJECT TERMS
Acoustical Scattering, Ray Methods, Elastic Shells, Bubbles, Plates, Particle Suspensions, Nonlinear Acoustics, Rayleigh Waves

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GEOMETRICAL ASPECTS OF SCATTERING AND PHYSICAL EFFECTS OF SOUND

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June 1996

Annual Summary Report for Grant N00014-92-J-1600

1 June 1995 - 31 May 1996

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Prepared for: **Office of Naval Research**
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TABLE OF CONTENTS

The project description, approaches, and summary of accomplishments are grouped according to Projects I, II, III, and IV.

I. A. Project Description: Transient and High-Frequency Enhancements in Scattering from Elastic Objects -- The objective is to identify physical processes that are likely to be important for the classification of scatterers in water based on high frequency scattering signatures. When possible, quantitative ray approximations are formulated to predict scattering amplitudes and experiments are used to test the approximations. The research will also give insight into scattering processes for scatterers at interfaces.

B. Approaches Taken: Leaky waves guided along the surface of the scatterer are investigated and modeled by extensions of Marston's formulation [JASA *97*, 34-41 (1995)]. One specific process being studied involves the excitation of guided waves that reflect off of the end of tilted cylinders to produce large backscattering signatures for certain ranges of aspect angles. Impulse responses are measured as a function of aspect angle using an improved version of the PVDF sheet source originally described in Kaduchak, Kwiatkowski, and Marston [JASA *97*, 2699-2708 (1995) and 1995 Annual Report pp. 4-15]. These are compared with recent approximate partial wave series (PWS) calculations for finite cylinders by G. Kaduchak (at ARL-UT Austin). Tone burst measurements are also taken, especially in the case of Karen Gipson's study of retroreflective backscattering due to Rayleigh waves on elastic solids with square corners.

Related investigations include scattering processes for elastic and fluid objects of variable thickness, including a novel exact PWS formulation [JASA (abstract) *98*, 2928 (1995)] and ray approximations which account for focusing of internal reverberations.

C. Accomplishments:

- Measurements were taken by Scot Morse of the impulse response of an empty thick cylindrical shell in water as a function of aspect angle [JASA (abstract) *99*, 2544 (1996)]. The measurements clearly show the frequency locus of a backscattering enhancement as a function of aspect angle extending to near end-on incidence. Appendix A of this report gives a summary which identifies a generalization of the lowest antisymmetric leaky Lamb wave as the corresponding contributor. The measurements are significant since related enhancements previously reported for aspect angles much closer to broadside have been shown to significantly enhance target visibility in a high-frequency imaging sonar [Kaduchak et al., JASA (accepted for publication)]. Morse has also experimentally

detected other high frequency backscattering enhancements associated with leaky wave propagation along the tilted cylinder which give end reflections.

- A more general spatial convolution formulation of the quantitative ray theory of such leaky wave scattering processes was developed by embedding Marston's previous two-dimensional formulation into three dimensions. The formulation is based on a Laurent expansion of leaky wave contributions to the reflection coefficient. (The formulation does not make use of thin shell assumptions for the local leaky wave mechanics.) The new formulation uses a two-dimensional surface convolution and was first tested by recovering several previously known special cases for leaky waves. For circular cylinders, these include scattering amplitudes, elliptical Fresnel coupling patches [Marston, JASA *96*, 1893-1898 (1994)], and the ray coupling conditions as a function of tilt. The new formulation explains how tilted cylinders with abrupt ends can have leaky wave backscattering enhancements similar in magnitude to signals associated with broadside reflections. The relevant ray paths do not involve repeated circumnavigations, and the enhancements are not associated with phenomena usually described as resonances.
- In related work, Karen Gipson has identified ways of improving the analysis of the retroreflective mechanism for enhanced backscattering due to leaky waves on a solid rectangular block with corners (1995 Annual Report, p. 16). Scot Morse analyzed the stability of rays reverberating between nonconcentric surfaces within a thick shell and predicted that a far-field focusing in the surrounding water can be produced which is periodic in the number of internal reflections. An approximate description of such periodic focal enhancements was developed using the Pearcey integral, and the existence of periodic foci was confirmed by measuring the backscattering of ultrasonic tone bursts by large glass lenses in water [JASA (abstract) *99*, 2544 (1996)].

II. A. Project Description: Interaction of Sound with Sound Mediated by a Suspension of Particles -- The objective of this project is to understand the large effects that suspended particles can have on the interaction of sound with sound in water. Since large acoustic signatures are observed even with very small volume fractions ϕ of suspended particles, the interaction may have practical applications for the measurement of ϕ or the particle compressibility. More generally, the interaction process is of a class that has previously been ignored in nonlinear acoustics.

B. Approaches Taken: Two acoustic signatures of the suspension are investigated: (i) the Bragg scattering from particle layers induced by the radiation pressure of a standing wave resonator due to the migration of the particle positions; (ii) the shift in the resonance

frequency of an ultrasonic standing wave as a result of the particle migration. The acoustic signatures in (i) are predicted to be much larger than for incoherent scattering from suspended particles since when particles migrate to pressure nodes (or antinodes) of the standing pump wave and the Bragg condition for the probe wave is met, all of the particles scatter with the same phase modulo (2π) [Simpson and Marston, JASA *98*, 1731-1741 (1995) and submitted to *Physical Acoustics*]. Our current method of measuring the Bragg scattering uses a probe wave that is collinear with the pump wave.

C. Accomplishments:

- Chris Kwiatkowski has measured and modeled the amplitude of the collinear Bragg signal as a function of parameters in the probe signal including frequency, duration, and bounce number of the reverberating probe signal. An extended range of suspension compositions and volume fractions have been tested including: polystyrene particles, glass particles, and bubbles [JASA (abstract) *99*, 2560 (1996)]. For small volume fractions ϕ, the measured reflectivity at the Bragg condition increases linearly with ϕ and probe duration and approximately linearly with bounce number, in general agreement with theory based on a Born approximation. A more general theory has been formulated based on transfer matrices. A skewed frequency response has been measured at large volume fractions of particles ($\phi \approx 0.01$).
- Kwiatkowski has also measured the downward shift in the pump wave resonance frequency resulting from banding of particles in water in an ultrasonic standing wave resonator. The resonance frequency is originally measured with a spatially uniform particle distribution at low standing wave amplitudes. The frequency shift was modeled using the Boltzmann-Ehrenfest principle of adiabatic invariance. The effect of the position of a single particle on the resonant frequency is described by Putterman et al. [JASA *85*, 68-71 (1989)] for a simpler problem. The analysis was modified to the present situation of a suspension of compressible particles. The typical frequency shift for a dilute suspension with $\phi = 0.001$ is 130 Hz for a 800 kHz resonance. The shift is typically within 20% of predictions.

III. A. Project Description: Electromagnetic Excitation of Elastic Modes of a Shell -- The objective is to determine whether oscillating magnetic fields can be used to excite specific modes of electrically conducting shells so as to produce easily detectable acoustic radiation in the surrounding fluid. This type of transduction has potential application to mode spectroscopy of fluid loaded shells where exact mode solutions are not known and to hybrid electromagnetic - acoustic object detection.

B. Approach: The excitation of modes with the Lorentz force on eddy currents in the pressure of a large static bias magnetic field is first used to measure the frequency of specific modes of interest of a shell in air. The acoustic radiation is detected by a microphone. (This linear coupling is analogous to the one used by Matula and Marston to excite flexural waves on a plate [JASA *97*, 1389-1398 (1995)]). Evaluation of the Maxwell electromagnetic stress tensor shows that even in the absence of a static bias field, an oscillating magnetic field B produces oscillating stresses. Since the stress is proportional to B^2, the stress oscillates at twice the frequency of the oscillating field.

C. Accomplishments:

- B. T. Hefner confirmed both the direct (Lorentz-force) coupling at the frequency f of the oscillating field and also the second-order (Maxwell) coupling at frequency 2f [JASA (abstract) *99*, 2594 (1996)]. The lowest frequency mode of a spherical shell was excited, which was a quadrupole quasiflexural mode near 64 kHz. In the absence of a static bias field, an f near 32 kHz was needed to observe the desired Maxwell coupling.

IV. A. Project Description: Monopole Mode of a Bubble Excited by Oscillating Electric Fields -- While the monopole response of bubbles to incident acoustic fields is relevant to a number of naval technologies, it can be difficult to directly measure the resonance response and damping of single bubbles. The objective of this project is to determine whether the monopole mode of bubbles in insulating liquids may be directly excited with oscillating electric fields. This would provide a new method of exploring bubble response and acoustic radiation for situations where the mode damping and frequency can not be directly calculated.

B. Approach: A dielectrophoretic levitator is used to trap bubbles in a low viscosity electrically insulating oil. An oscillating tone burst voltage is superposed on the static levitation voltage and any resulting acoustic radiation is detected with a hydrophone in the oil bath. Analysis of the general form of Maxwell stresses on the bubble indicates that the bubble should primarily oscillate at the same frequency as the applied tone burst.

C. Accomplishments:

- Experiments carried out with Dr. D. B. Thiessen confirmed the existence of the desired coupling [JASA (abstract) *99*, 2560 (1996)]. The measurements were taken for bubbles having radii between 0.5 and 2 mm giving monopole frequencies between 7 kHz and 2 kHz, which are near the predicted values. The response was maximized when the tone

burst frequency was at resonance. The observed ring-down of the signature after the excitation suggests that the method could be used to measure damping in a sufficiently larger tank of liquid where reverberations could be neglected.

- The proper detailed form of stress tensor for determining the strength of the coupling at a dielectric interface due to an oscillating field is a controversial subject. This is because in some types of experiments the Helmholtz contribution appears to be canceled by the electrostrictive response of the liquid. The radial projection of the oscillating stress and the resulting bubble responses were calculated for certain cases. Assuming the aforementioned cancellation, the projection gives the same value as the electric field contribution to the pressure calculated by Marston and Apfel by another method [Physics Letters *60A*, 225-226 (1977)]. While our measurements of the bubble response are presently not able to discriminate between different models of the coupling, that should not prevent the method from being used to measure bubble mode frequency and decay.

OFFICE OF NAVAL RESEARCH
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS REPORT
for
01 June 95 through 31 May 96

Contract/Grant Number: N00014-92-J-1600

Contract/Grant Title: Geometrical Aspects of Scattering and Physical Effects of Sound

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a.	Number of papers submitted to refereed journals but not yet published:	1
b.	Number of papers published in refereed journals (ATTACH LIST):	3
c.	Number of books or chapters submitted but not yet published:	1
d.	Number of books or chapters published (ATTACH LIST):	0
e.	Number of printed technical reports & non-refereed papers (ATTACH LIST):	1
f.	Number of patents filed:	0
g.	Number of patents granted (ATTACH LIST):	0
h.	Number of invited presentations at workshops or professional society meetings:	3
i.	Number of contributed presentations at workshops or professional society meetings:	8
j.	Honors/awards/prizes for contract/grant employees, such as scientific society and faculty awards/offices (ATTACH LIST):	2
k.	Number of graduate students supported at least 25% this year this contract/grant:	4
l.	Number of post docs supported at least 25% this year this contract/grant:	1

How many of each are females or minorities? These six numbers are for ONR's EEO/Minority Reports. Minorities include Blacks, Aleuts, Amindians, etc., and those of Hispanic or Asian extraction/nationality. The Asians are singled out to facilitate meeting reporting semantics re "underrepresented".

Graduate student FEMALE:	1	Post doc FEMALE:	
Graduate student MINORITY:		Post doc MINORITY:	
Graduate student ASIAN E/N:		Post doc ASIAN:	

1996 P3H Report Supplement for Grant N00014-92-J-1600

b. Papers Published in Refereed Journals:

1. H. J. Simpson and P. L. Marston, "Ultrasonic four-wave mixing mediated by an aqueous suspension of microspheres: theoretical steady-state properties," J. Acoust. Soc. Am. **98**, 1731-1741 (1995).

2. P. L. Marston, "Variable phase coupling coefficient for leaky waves on spheres and cylinders from resonance scattering theory, "Wave Motion **22**, 65-74 (1995).

3. G. Kaduchak and P. L. Marston, "Traveling-wave decomposition of surface displacements associated with scattering by a cylindrical shell: Numerical evaluation displaying guided forward and backward wave properties," J. Acoust. Soc. Am. **98**, 3501-3507 (1995).

c. Printed Technical Reports & Non-refereed Papers:

1. P. L. Marston, "Scattering and radiation of high frequency sound in water by elastic objects, particle suspensions, and curved surfaces," Annual Summary Report for ONR Grant N00014-92-J-1600 (issued June, 1995).

j. Honors/awards/prizes for contract/grant employees:

1. S. F. Morse, Third-place award from the Acoustical Society of America in the 1995/96 Annual "Best Student papers in Structural Acoustics and Vibration," competition based on his paper and presentation: "Backscattering due to ray reverberations between nonconcentric surfaces of a thick shell: ray stability, transitions in wavefront shapes, and observed scattering enhancements due to focusing."

2. P. L. Marston, President of the Inland Northwest Acoustical Society of America Chapter (1995 - Spring 1996).

k and l. Total Number of Graduate Students and Post Docs Supported at Least 25% This Year on This Grant.

Graduate Students: 4

Karen Gipson
Chris Kwiatkowski
Scot Morse
Brian T. Hefner

Post Docs: 1

David Thiessen

Appendix A: Elastic Contribution to the High-Frequency Backscattering by a Thick Cylindrical Shell Extending to Near End-On Incidence

Figure 1 shows the scattering geometry under consideration where from symmetry a single aspect angle γ characterizes the target orientation; $\gamma = 0°$ corresponds to broadside illumination. A plausible leaky wave ray contribution is also shown where for strong excitation of the leaky wave $\sin\gamma \approx c/c_l$, where c_l is the leaky wave phase velocity at a specified frequency and c is the speed of sound in water. The existence of such enhancements for large γ (near 90°) may be important to enhancing the target visibility of cylinders when viewed from a significant distance in shallow water. The ray mechanism shown should be present at frequencies slightly above the coincidence frequency from the generalization of the supersonic branch of the lowest antisymmetric a_0^+ leaky Lamb wave.

The experimental set up to test for such contributions is shown in **Fig. 2** where the PVDF sheet produces a pressure impulse [Kaduchak, Kwiatkowski, and Marston, JASA *97*, 2699-2708 (1995) and 1995 Annual Report]. The aspect angle is computer controlled by a stepper motor. **Figure 3(a)** shows the spectral magnitude of the measured impulse response as a function of frequency and aspect angle. The initial specular reflection from the end of the cylinder closest to the source is time gated out of each record prior to evaluation of the spectrum. The wave-number radius product ka has a value of 10 at a frequency of 112 kHz in this experiment. **Figure 3(a)** shows a clear ridge of enhanced backscattering extending from the right near γ of 40° to γ near 90°. **Figure 3(b)** shows that this ridge is the result of the a_0^+ leaky Lamb wave contribution with the ray diagram shown in **Fig. 1**. The curve shown in **Fig. 3(a)** is $\gamma = \sin^{-1}(c/c_l)$ where c_l is the calculated for the a_0^+ wave on a water-loaded plate having the same thickness as the shell.

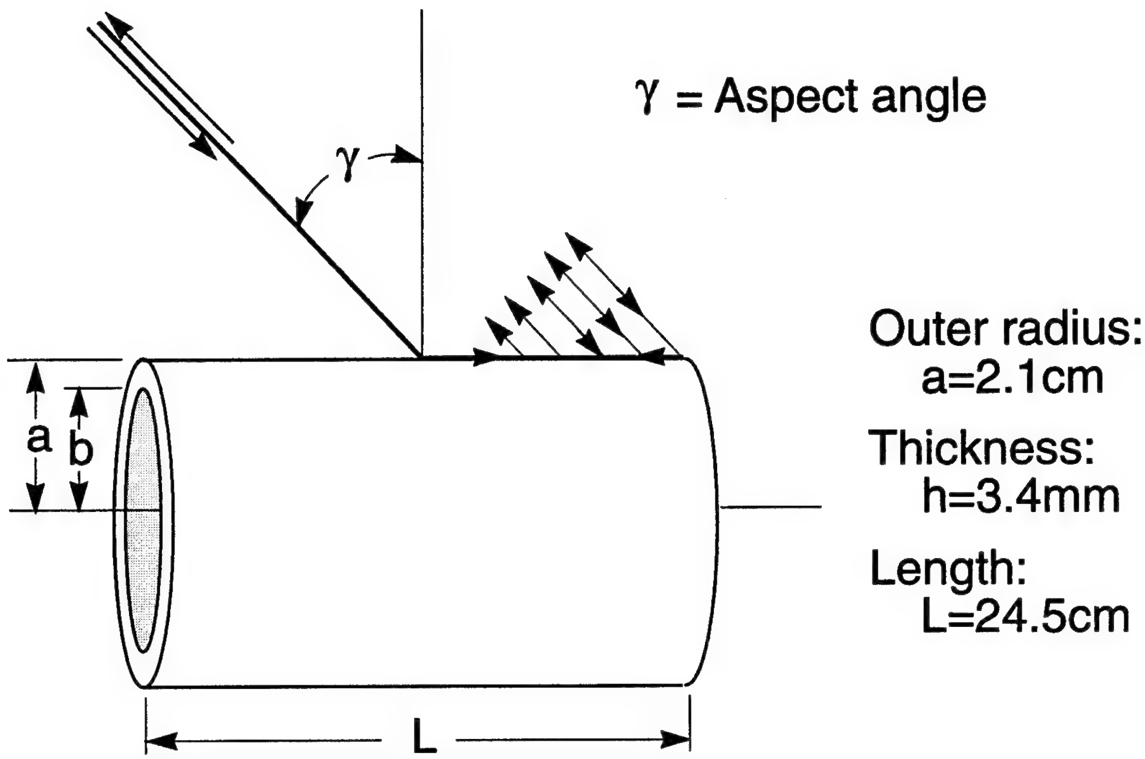

Figure 1

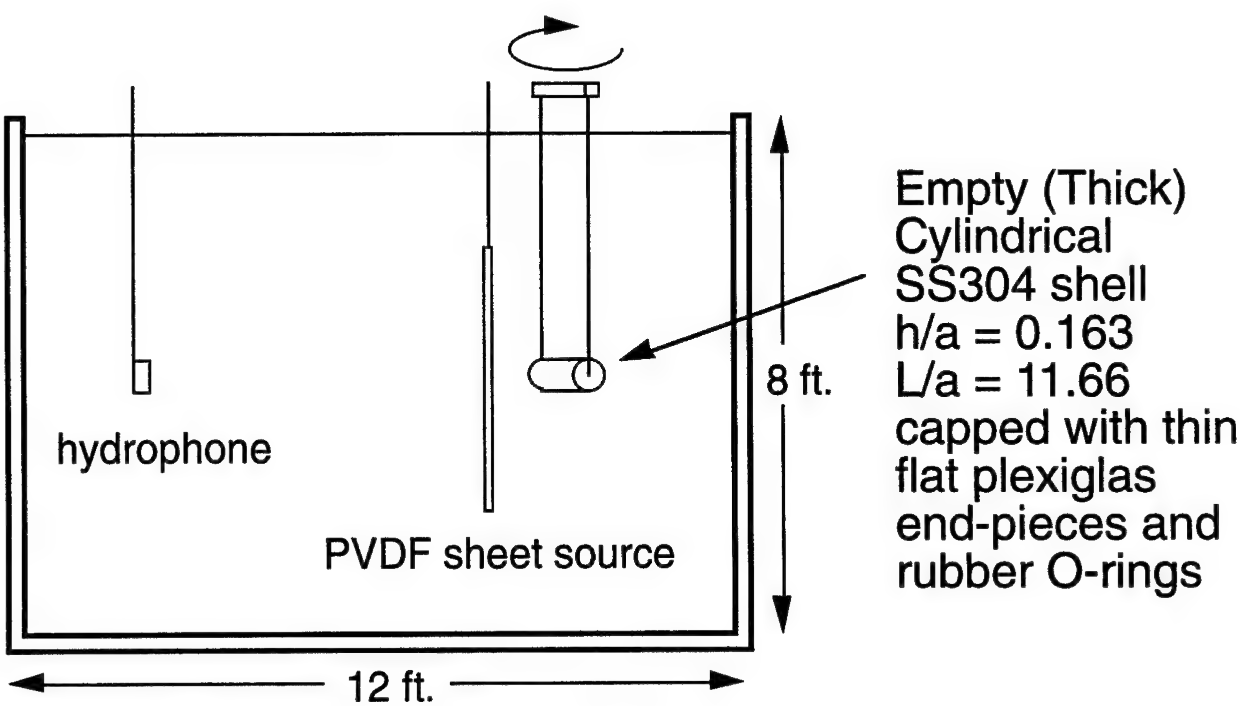

Figure 2

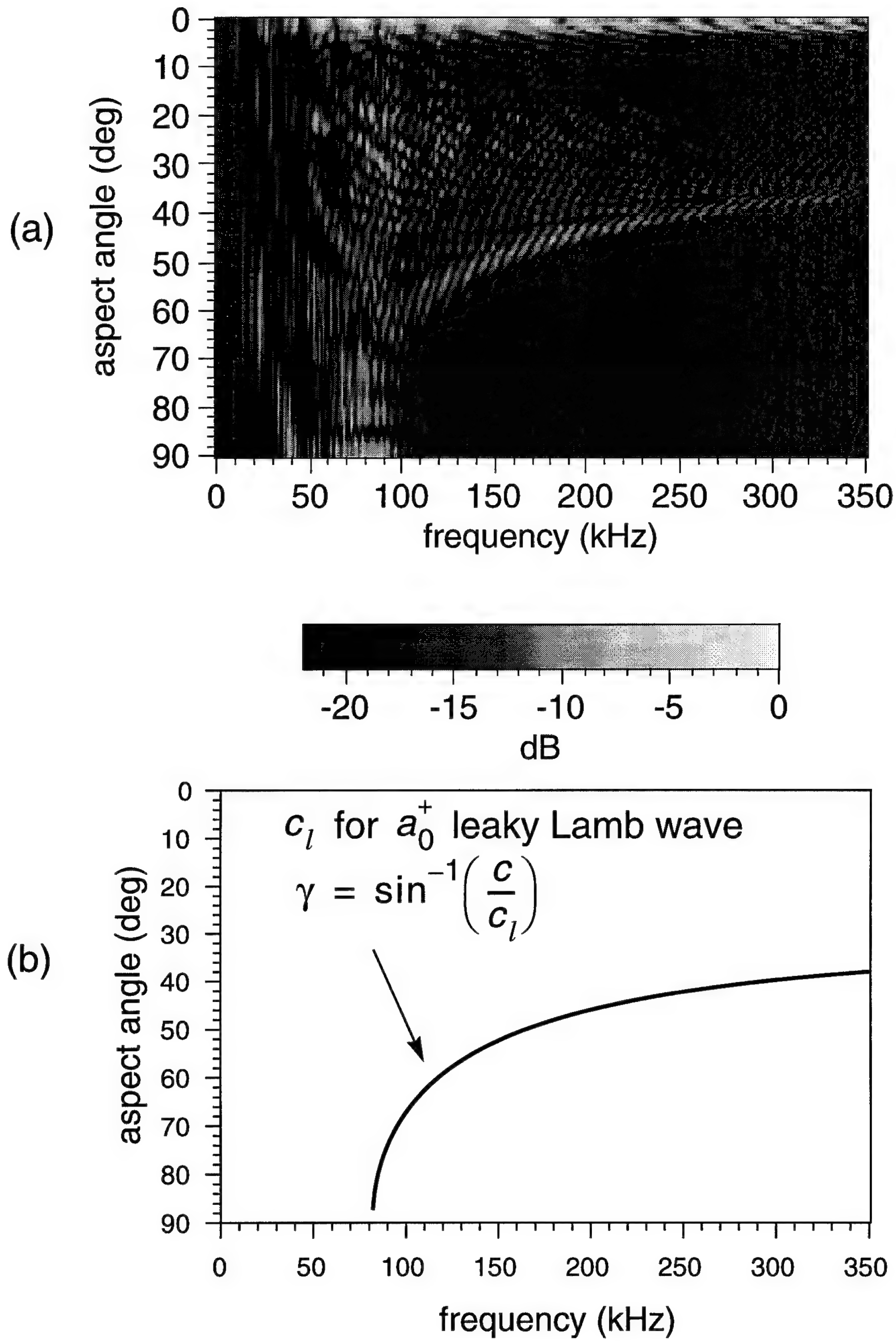
(a)
aspect angle (deg)
frequency (kHz)
dB
(b)
c_l for a_0^+ leaky Lamb wave
$\gamma = \sin^{-1}\left(\frac{c}{c_l}\right)$
aspect angle (deg)
frequency (kHz)

Figure 3

Appendix B: Research Results from Other Grants or Sponsors

For convenience, some recent publications from Marston's program sponsored by other grants are listed below:

1. T. J. Asaki, D. B. Thiessen, and P. L. Marston, "Effect of an insoluble surfactant on capillary oscillations of bubbles in water: Observation of a maximum in the damping," Phys. Rev. Lett. *75*, 2686-2689 (1995); *75*, 4336 (E) (1995).

2. T. J. Asaki and P. L. Marston, "Free decay of shape oscillations of bubbles acoustically trapped in water and sea water," J. Fluid Mech. *300*, 149-167 (1995).

3. S. F. Morse, D. B. Thiessen, and P. L. Marston, "Capillary bridge modes driven with modulated ultrasonic radiation pressure," Phys. Fluids *8*, 3-5 (1996).

In the following report, Mark J. Marr-Lyon presented the results of observations of single bubble sonoluminescence (SBSL) in magnetic fields up to 0.6 T:

Mark J. Marr-Lyon, "The effect of magnetic fields on a sonoluminescing bubble," M.S. Degree Project Report (December 1995).

The SBSL of a bubble in water could be easily observed by eye but there were no obvious effects of the B field detectable with available instrumentation.

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